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SILICON MONOXIDE: DETECTION OF MASER EMISSION FROM THE SECOND VIBRATIONALLY EXCITED STATE

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ABSTRACT

The $J = 1$–0 rotational transition of the second vibrational state ($v = 2$) of SiO has been detected in late M-type variable stars and in the center of the Orion Nebula. This transition of SiO requires 3520° K of excitation for pumping the observed maser line. The ground ($v = 0$) and third ($v = 3$) vibrational states were not detected.

Subject headings: masers — molecules — Orion Nebula — variable stars

In 1973 December we detected maser emission from the center of the Orion Nebula which we suggested might be a rotational transition ($v = 1$, $J = 2$–1) in the first vibrationally excited state of silicon monoxide (Snyder and Buhl 1974*a*). With the subsequent detection of two more rotational transitions of SiO ($v = 1$, $J = 3$–2; and $v = 1$, $J = 1$–0) this identification was confirmed (Davis *et al.* 1974; Thaddeus *et al.* 1974). During 1974 January and March we made a survey of sources of maser emission from SiO ($v = 1$, $J = 2$–1) at 3.5 mm wavelength and found that the only sources of this line outside of Orion were a number of late M-type variable stars, many of which have OH and H_2O maser emission (Kaifu, Buhl, and Snyder 1974).

In this *Letter* we report on the detection of the second vibrationally excited state of SiO ($v = 2$, $J = 1$–0) as well as the first vibrationally excited state ($v = 1$, $J = 1$–0) in a number of sources. The observations were made from 1974 June 1 to June 4 with the 36-foot (11 m) telescope of the National Radio Astronomy Observatory at Kitt Peak. A 7-mm-wavelength mixer receiver was used which has a single-sideband system temperature of 1500° K. The spectra were taken with a 256-channel filter bank which has a resolution of 100 kHz corresponding to a velocity resolution of 0.7 km s^{-1}. Temperature calibration was done with a chopping wheel in front of the feed. This method of calibration corrects for telescope blockage, ohmic loss, and feed spillover, yielding an antenna temperature T_a^* (Ulich 1974). Observations of Orion were done with the dome blocking the telescope to prevent solar heating of the surface. Hence, the temperature scales displayed for Orion have been increased by 1.67 to correct for dome loss. Other sources were observed through the open slit of the dome. Velocities in this paper are given with respect to the local standard of rest. The aperture efficiency of the telescope at this wavelength is 50 percent, and the half-power beamwidth is 160″.

We made observations on the first three vibrationally excited states of ^{28}SiO ($v = 1$, 2, and 3, $J = 1$–0) as well as the ground state ($v = 0$, $J = 1$–0). The frequencies for these transitions are 43.122 GHz ($v = 1$), 42.82051 GHz ($v = 2$) (Lovas 1974), 42.51933 GHz ($v = 3$), and 43.42379 GHz ($v = 0$) (Lovas and Krupenie 1974). All of the frequencies have been measured in the laboratory. The first vibrationally excited state is 1231 cm^{-1} above the ground state, the second is 2449 cm^{-1} above the ground state, and the third is 3655 cm^{-1} above the ground state. These correspond to thermal excitation temperatures of 1770°, 3520°, and 5260° K, respectively.

In figure 1 we show the spectra obtained for the $v = 0$, 1, 2, and 3, $J = 1$–0 transitions of SiO in the star W Hya, an M8e variable, which also exhibits OH and H_2O maser emission (Wilson 1973; Schwartz and Barrett 1970). In this star the $v = 1$ and 2 lines of SiO are present in about equal intensity while the $v = 0$ and 3 lines are at least a factor of 20 weaker. The temperature scales for the $v = 0$ and 3 lines are expanded by a factor of ~10 to show the noise level. The negative results for these lines represent an integration time of 60 and 20 min, respectively. This star had the largest peak intensity of any star surveyed at 3.5 mm (Kaifu *et al.* 1974); however, we did not look at *o* Cet (Mira). The 3.5-mm spectrum for W Hya ($v = 1$, $J = 2$–1) shows a main peak ($T_a^* = 10°$ K) at +39 km s^{-1} (velocity width = 5 km s^{-1}) with a smaller blended peak at +44 km s^{-1} ($T_a^* = 2°$ K). In figure 1 the $v = 1$, $J = 1$–0 line shows mainly the +39 km s^{-1} feature with a slightly asymmetric profile indicating the presence of

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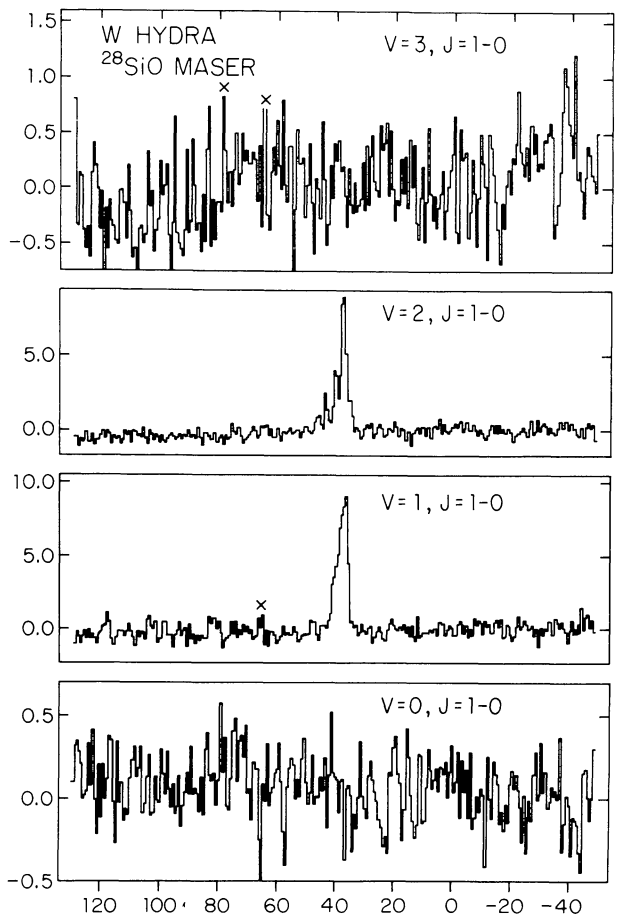

FIG. 1.—The v = 0, 1, 2 and 3 vibrational states of SiO in W Hya. The horizontal scale is radial velocity in km s^{-1} with respect to the local standard of rest. The vertical scale is antenna temperature T_A^* in degrees K. × marks channels which are not operating.

the +44 km s^{-1} feature. At the v = 2, J = 1–0 line, the profile is narrower with a suggestion of the higher-velocity component. Both this star and VY CMa show strong emission from the second vibrational state ($v = 2 \geq v = 1$).

In figure 2 we show the spectra obtained for the stars VY CMa, R Leo, *o* Cet (Mira), and the Orion Nebula. In the case of VY CMa, R Leo, and Orion the spectra obtained here are similar but not identical to the spectra obtained in the 3.5-mm survey (Kaifu *et al.* 1974 and Snyder and Buhl 1974*a*). For VY CMa the 3.5-mm data show a main peak at +10 km s^{-1} (T_a^* = 4° K), a smaller peak at +30 km s^{-1} (T_a^* = 1° K), and several smaller blended features. The profiles shown here for the v = 1 and 2, J = 1–0 lines indicate much narrower well-separated features with velocities of +25, +12, and +5 km s^{-1}. The lines in the v = 2, J = 1–0 spectrum are narrower than the v = 1, J = 1–0 lines, with the strong line at +12 km s^{-1} being stronger ($v = 2 > v = 1$) and the weak components at +25 and +5 km s^{-1} being weaker ($v = 2 < v = 1$).

R Leonis at 3.5 mm (v = 1, J = 2–1) shows a sharp feature at +7 km s^{-1} (T_a^* = 5° K) on top of a broader (velocity width = 10 km s^{-1}) blended component. The v = 1 and 2, J = 1–0 lines shown in figure 2 exhibit separate velocity components at 0 km s^{-1} and +7 km s^{-1}, with the v = 2 lines being weaker than the v = 1 lines. Mira (*o* Cet) had the highest peak intensity of any of the sources we surveyed for the v = 1, J = 1–0 transition (Snyder and Buhl 1974*b*). The v = 1, J = 1–0 line (T_a^* = 30° K) is a very narrow feature, only one channel wide. Since this feature is unresolved, its peak intensity is probably much larger than 30° K (we did not observe this star in the 3.5-mm survey). The present data indicate a single intense line at +45 km s^{-1} with some much weaker components toward lower velocities. The v = 2 line is a factor of 4 weaker than the v = 1 line, and the v = 3 line is at least a factor of 20 weaker than the v = 2 line. We also attempted to detect the ^{29}SiO isotope line (v = 1, J = 1–0), without success. It is at least a factor of 50 weaker than the ^{28}SiO line (the cosmic abundance ratio ^{28}Si/^{29}Si = 19.6).

The SiO maser in the Orion Nebula is coincident in position with the OH and H_2O masers and with the Kleinmann-Low infrared nebula. The v = 1, J = 2–1 spectra of this source show a number of components which are blended around two major features at +16 and −7 km s^{-1}. (The peak intensities are T_a^* = 13° K and T_a^* = 8° K, respectively.) The present data give for the v = 1 and 2, J = 1–0 lines two major components at velocities of +16 and −6 km s^{-1}. The v = 1, J = 1–0 components are about the same width as the v = 1, J = 2–1 lines but have an intensity of T_a^* = 30° K and T_a^* = 12° K, respectively. One peculiarity in the v = 2, J = 1–0 spectra is that the relative intensity of the two components is reversed, with the −6 km s^{-1} feature being stronger and the velocity width being wider and more blended. Orion, R Leo, and *o* Cet all have weaker J = 1–0 emission from v = 2 than from v = 1.

In table 1 we summarize the results of our study of SiO. It is clear that the observed narrow line profiles, multiple structure, and peculiar intensity ratios characterize an SiO maser, and the observations put restrictions on the type of pumping models which are responsible for this emission. The first is that the v = 1, J = 2–1 transition is generally wider and more blended than the v = 1, J = 1–0 transition which shows some pumping selection between these two rotational transitions. In two of the sources, W Hya and VY CMa, the intensity of the v = 2 state was equal to or stronger than the v = 1 state. However, in the case of W Hya the v = 3 state is at most the weak $T_a^* \sim 0.2$° K feature buried in the noise of figure 2. Several states expected under normal Boltzmann statistics are missing. The v = 3 state has not been detected yet, and the v = 0 state does not appear in the one source we examined. In addition the v = 2, J = 2–1 transition was not detected in a search of the sources during the 3.5-mm observing period. Hence it appears that any pumping model must invert mainly the J = 1–0, v = 1 and 2 transitions along with the v = 1, J = 2–1 and

$J = 3$–2 transitions. The transitions of $v = 0$ and $v = 3$ are not excited along with the $v = 2, J = 2$–1 transition. Thus the missing transitions place quite severe restrictions on the pumping mechanism responsible for the observed maser emission.

The results summarized in table 1 suggest two possible excitation processes which involve resonant absorption by rotationally cool, $v = 0$, SiO. The simplest mechanism involves direct pumping of $v = 0$ SiO by the infrared radiation field of the central star (Gillett, Stein, and Solomon 1970) near 8 μ for the $v = 0$–1 and 1–2 transitions or near 4 μ for the $v = 0$–2 transition. This process would favor emission from the $v = 1$, $J = 1$ level, as observed. The second mechanism involves the participation of an electronically excited state—most likely the $A\ ^1\Pi$ could be formed by radiative association of the ground-state atoms or by absorption of ultraviolet radiation near 2300 Å, and the Franck-Condon effect would provide the necessary selective vibrational excitation in the ground state. A typical absorption cycle might occur as follows: ultraviolet absorption near 2257 Å ($X\ ^1\Sigma\ v = 0$–$A\ ^1\Pi\ v = 2$)

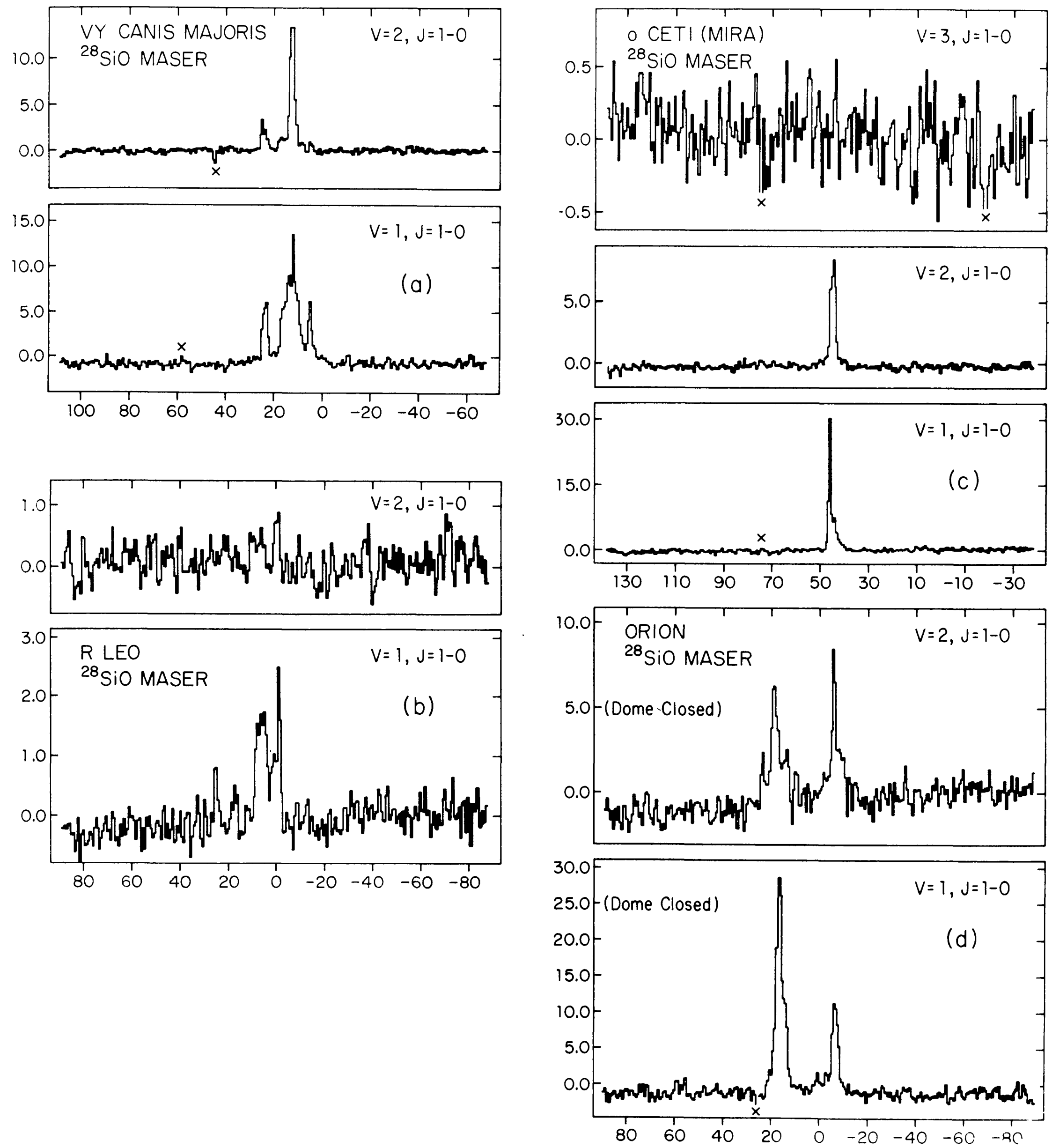

FIG. 2.—The $v = 1$ and 2 lines in the stars VY CMa and R Leo. The horizontal scale is radial velocity in km s^{-1}; the vertical scale is antenna temperature T_A^* in degrees K. The star *o* Cet (Mira) has the most intense $v = 1$ line, but does not show a $v = 3$ line. In the center of the Orion Nebula the line structure is very similar to the 3.5-mm observations (Snyder and Buhl 1974*a*). The Orion antenna temperature was corrected for dome attenuation.

TABLE 1

PEAK FLUX* AND ANTENNA TEMPERATURE FOR ^{28}SiO

Source	Velocity (km s^{-1})	$J = 1$–0				$J = 2$–1		$J = 3$–2†
		$v = 0$	$v = 1$	$v = 2$	$v = 3$	$v = 1$‡	$v = 2$	$v = 1$
W Hydrae..........	+39	<20(<.5)	355(8)	355(8)	<20(<.5)	530(10)	<10(<.2)	<200
VY Canis Majoris...	+25	...	265(6)	135(3)	...	50(1)	<15(<.3)	...
	+12	...	445(10)	620(14)	...	210(4)	<15(<.3)	...
	+ 5	...	265(6)	20(.5)	...	50(1)	<15(<.3)	...
R Leonis...........	+ 7	...	135(3)	20(.5)	...	270(5)	<50(<1)	...
	+ 0	...	180(4)	30(.7)	...	...	...	...
o Ceti (Mira).......	+45	...	1330(30)§	355(8)	<20(<.5)	...	...	...
Orion..............	+16	...	1330(30)	310(7)	...	690(13)	<30(<.5)	260
	− 6	...	530(12)	400(9)	...	430(8)	<30(<.5)	< 50

* Flux given in flux units or janskys: 10^{-26} W m^{-2} Hz^{-1}. (Antenna temperature T_a^* in ° K.)

† Thaddeus *et al.* 1974.

‡ Kaifu *et al.* 1974; Snyder and Buhl 1974*a*.

§ Observations of the $v = 1$, $J = 1$–0 transition of ^{29}SiO gave an upper limit of: <20(<.5).

followed by emission primarily to the $X\ ^1\Sigma\ v = 1, 2, 3$ states with some distribution over several low-J levels due to the $\Delta J = 0, \pm 1$ selection rule. The radiative association process appears less viable in that it would provide less specific vibrational excitation since SiO would be formed in very high v states. Both infrared and ultraviolet excitation processes could lead to substantial radiation trapping of the $v = 1 \rightarrow 0$ emission near 8 μ, thus maintaining the excitation of $v = 1$ SiO at low J. Observations of other v and J transitions may provide a means for distinguishing between the feasible mechanisms.

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